BOUT++ Simulations of Edge Turbulence in the Alcator C-Mod Tokamak

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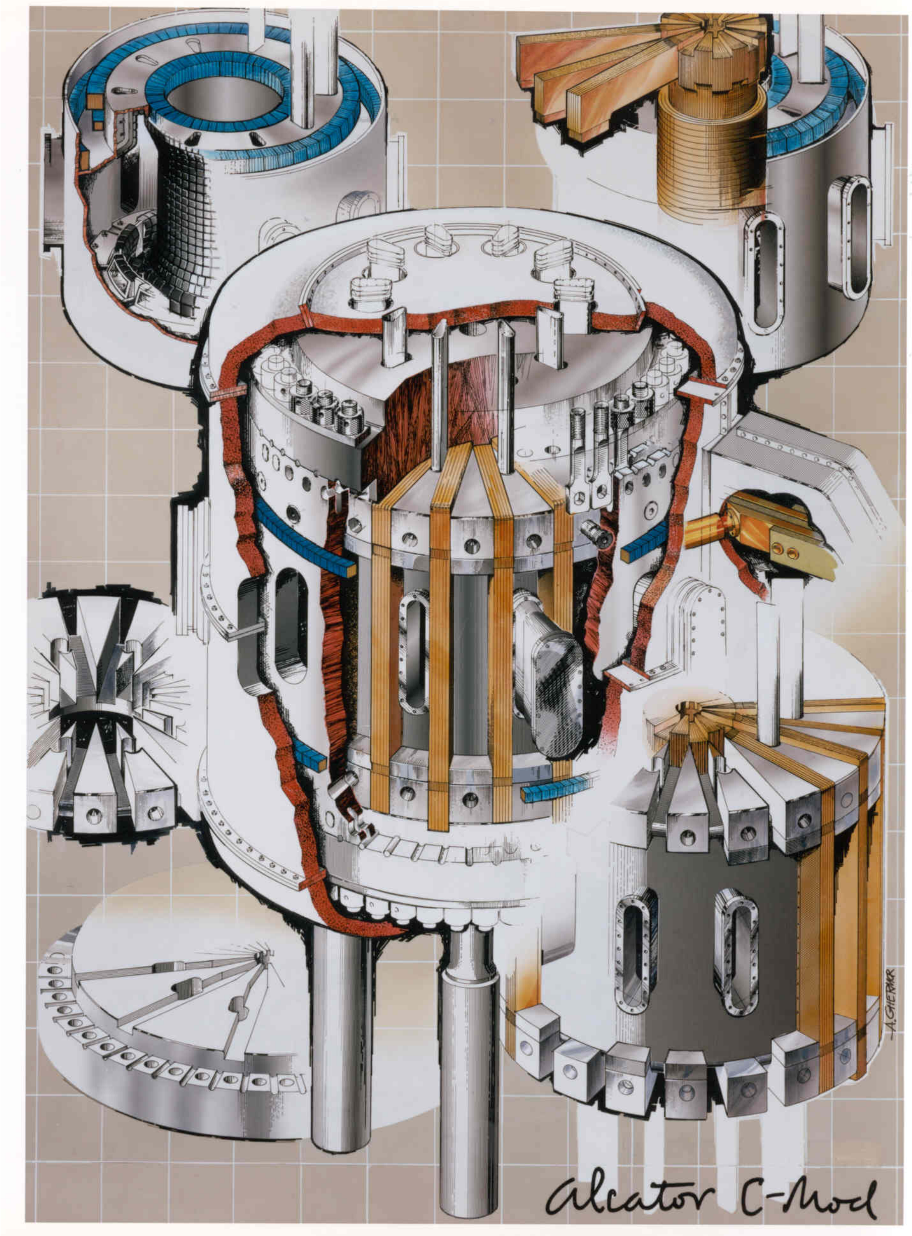
Outline

- Introduction
- Alcator C-Mod Overview
- Physics of the Peeling-Ballooning Module Sequentially Added to BOUT++ Simulations of C-Mod
  - Resistivity
  - Diamagnetic and ExB flow
  - Nonlinear Effects
- Conclusion and Future Work

Introduction

- Tokamak energy confinement is thought to be strongly controlled by plasma transport in the edge region just inside the last closed magnetic flux surface
  - A first principles understanding of this transport requires coupling between experiment and theory
- BOUT++ is capable of nonlinear fluid boundary turbulence analysis in a general geometry
  - Experimentally measured C-Mod profiles have been used as input for BOUT++ simulations

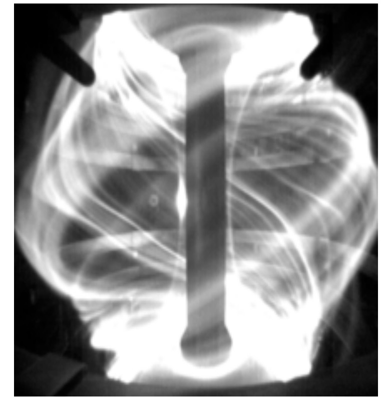
The Alcator C-Mod Tokamak



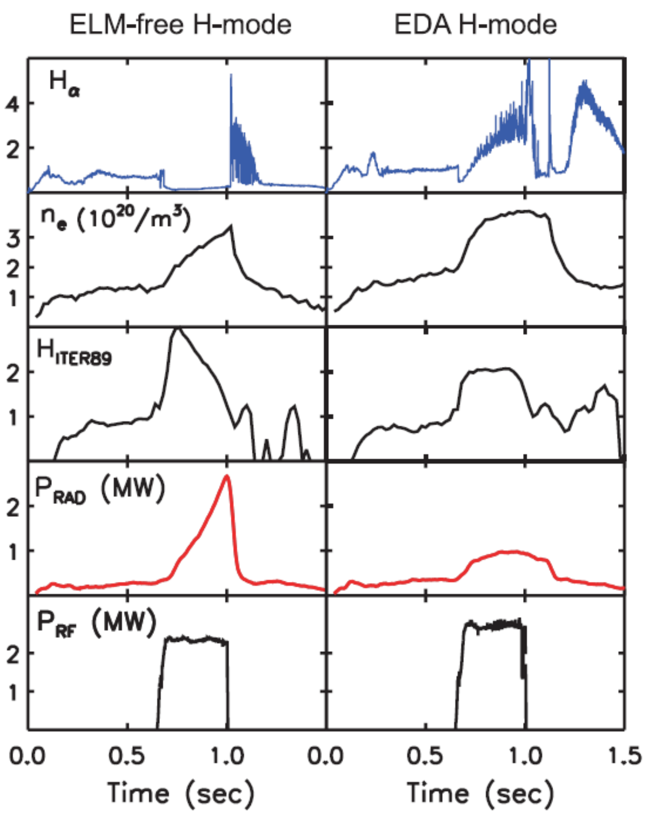
- Alcator C-Mod is a compact, high-field tokamak
  - $R = 0.66$ m, $a = 0.22$ m
  - $B < 8.1$ T
  - $n_e < 1 \times 10^{21}\ m^{-3}$
  - $I_p < 2$ MA
- Active Research
  - Heating and Current Drive
  - Plasma Transport
  - Edge and Divertor Physics
- Several confinement regimes are investigated on C-mod
  - H-mode
  - **I-mode**
  - L-mode
  - Linear Ohmic

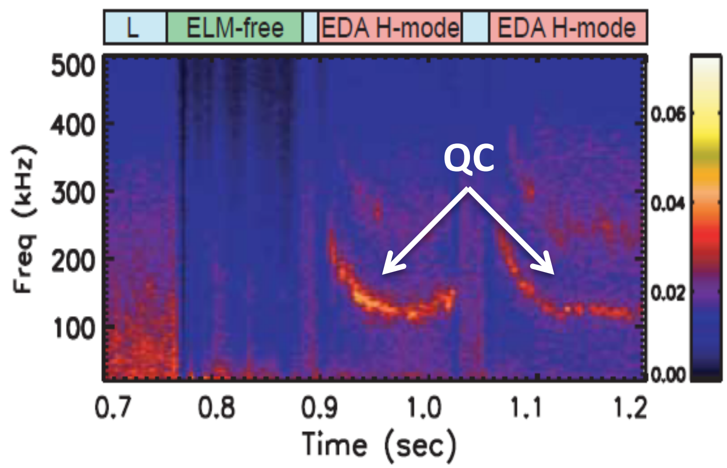
Edge Transport Strongly Influences Energy Confinement

- L-mode confinement is not likely to lead to a viable fusion reactor
- H-mode confinement is satisfactory for an economic fusion reactor
- Edge Localized Modes (ELMs) or other mild edge modes (Quasi-Coherent or Weakly Coherent Modes) reduce impurity accumulation and allow steady state H mode operation
- I mode is presently under investigation at C-Mod and elsewhere



An ELM in MAST



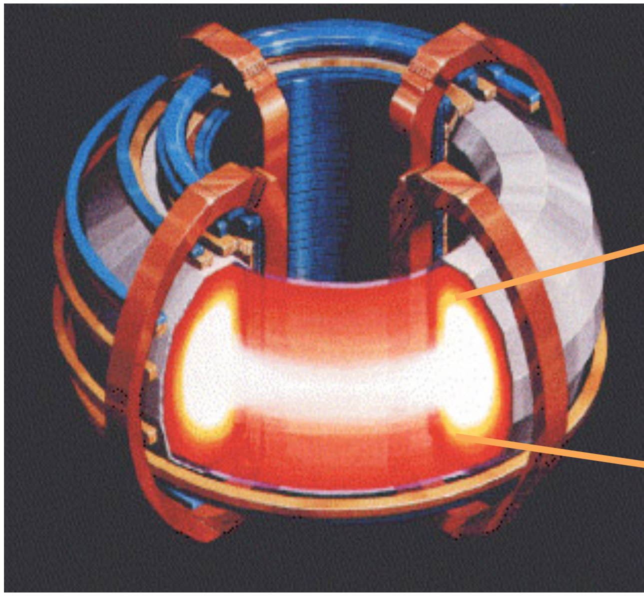


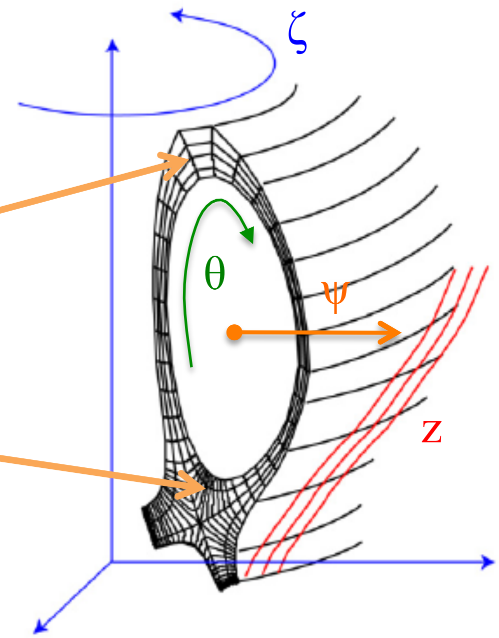
PCI measured density fluctuations in various confinement regimes

* M. Greenwald, et. al, *Fusion Sc. and Tech.*, **51**, 266, (2007)

- C-Mod's **enhanced D_α (EDA) H-mode** is relatively quiescent with good energy confinement and reduced impurity confinement
  - Pedestal regulated by a continuous quasi-coherent mode **(QCM)** oscillation between 50 - 200 kHz

Magnetic geometry in BOUT++ Edge Plasmas





Field-aligned coordinates

$$x = \psi - \psi_0,$$

$$y = \theta,$$

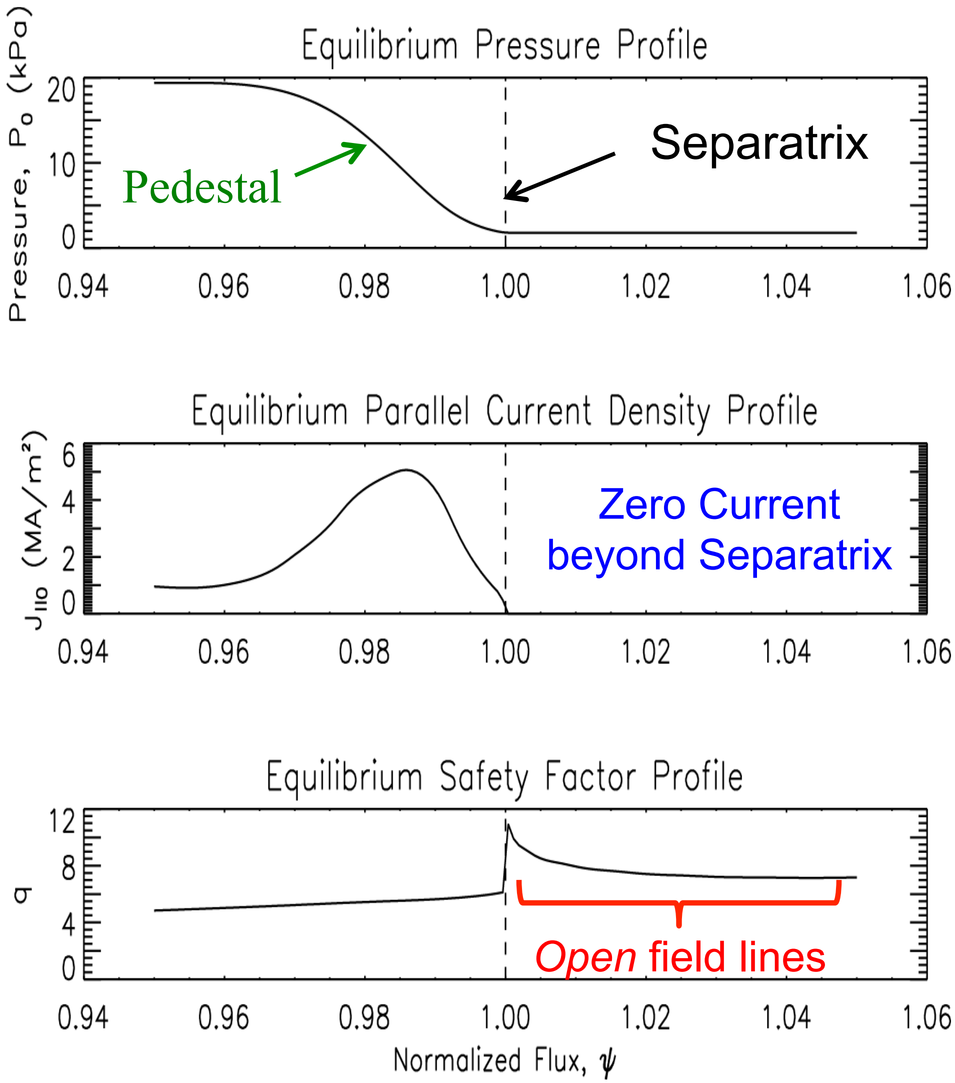
$$z = \zeta - \int_{\theta_0}^{\theta} \nu(\psi,\theta) d\theta$$

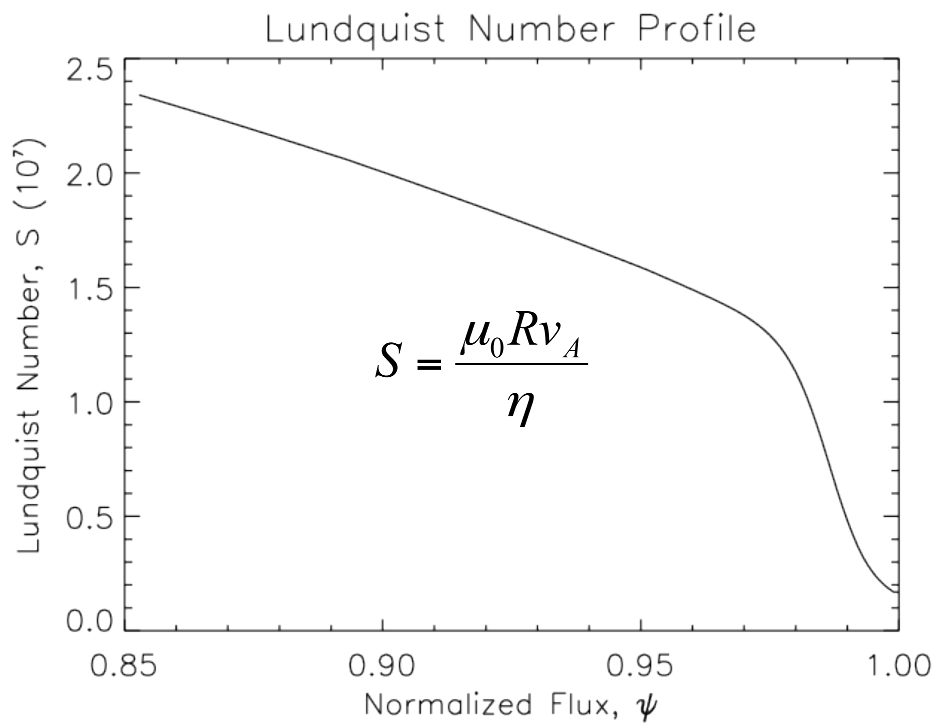
where ν is the local safety factor given by:

$$\nu(\psi,\theta) = \frac{\vec{B}\cdot\nabla\zeta}{\vec{B}\cdot\nabla\theta}$$

- Magnetic field topology changes from closed to open field lines across the separatrix
- In this talk, the edge refers to $0.95 < \psi < 1.05$ (~1 cm region in C-Mod)

C-Mod Equilibrium EDA H-Mode Parameters used as BOUT++ Input (1110201023.00900)





Lundquist Number (*S*) is a dimensionless ratio of the resistive diffusion time to the Alfvén time

– ***S* ~10⁷** in C-Mod EDA pedestal

The Nonlinear System of Equations for Simulating Non-Ideal MHD Peeling-Ballooning Modes

Reduced MHD Equations

Vorticity

$$\frac{\partial \varpi}{\partial t} + v_E \cdot \nabla \varpi = B_0^2 \nabla_{\parallel}\left(\frac{j_{\parallel}}{B_0}\right) + 2b_0 \times \kappa \cdot \nabla p,$$

Pressure

$$\frac{\partial P}{\partial t} + v_E \cdot \nabla P = 0,$$

Ohm's

$$\frac{\partial A_{\parallel}}{\partial t} = -\nabla_{\parallel}(\phi + \Phi_0) + \frac{\eta}{\mu_0}\nabla_{\perp}^2 A_{\parallel} - \frac{\eta_H}{\mu_0}\nabla_{\perp}^4 A_{\parallel},$$

Definitions

$$\varpi = \frac{n_0 M_i}{B_0}\left(\nabla_{\perp}^2 \phi + \frac{1}{n_0 Z_i e}\nabla_{\perp}^2 p_i\right), \quad P = P_0 + p$$

$$j_{\parallel} = J_{\parallel 0} - \frac{1}{\mu_0}\nabla_{\perp}^2 A_{\parallel}, \quad v_E = \frac{1}{B_0} b_0 \times \nabla(\phi + \Phi_0)$$

Non-ideal physics

✓Using resistive MHD term, resistivity can be renormalized as **Lundquist** Number

$$S = \mu_0 R v_A / \eta$$

✓Using hyper-resistivity η_H

$$S_H = \mu_0 R^3 v_A / \eta_H = S/\alpha_H$$

✓After gyroviscous cancellation, the diamagnetic drift modifies the vorticity and additional nonlinear terms

✓Using force balance and assuming no net rotation,

$$E_{r0} = (1/N_i Z_i e)\nabla_{\perp} P_{i0}$$

Non-Ideal Physics were Methodically Included in Simulations after Initial Ideal Simulations

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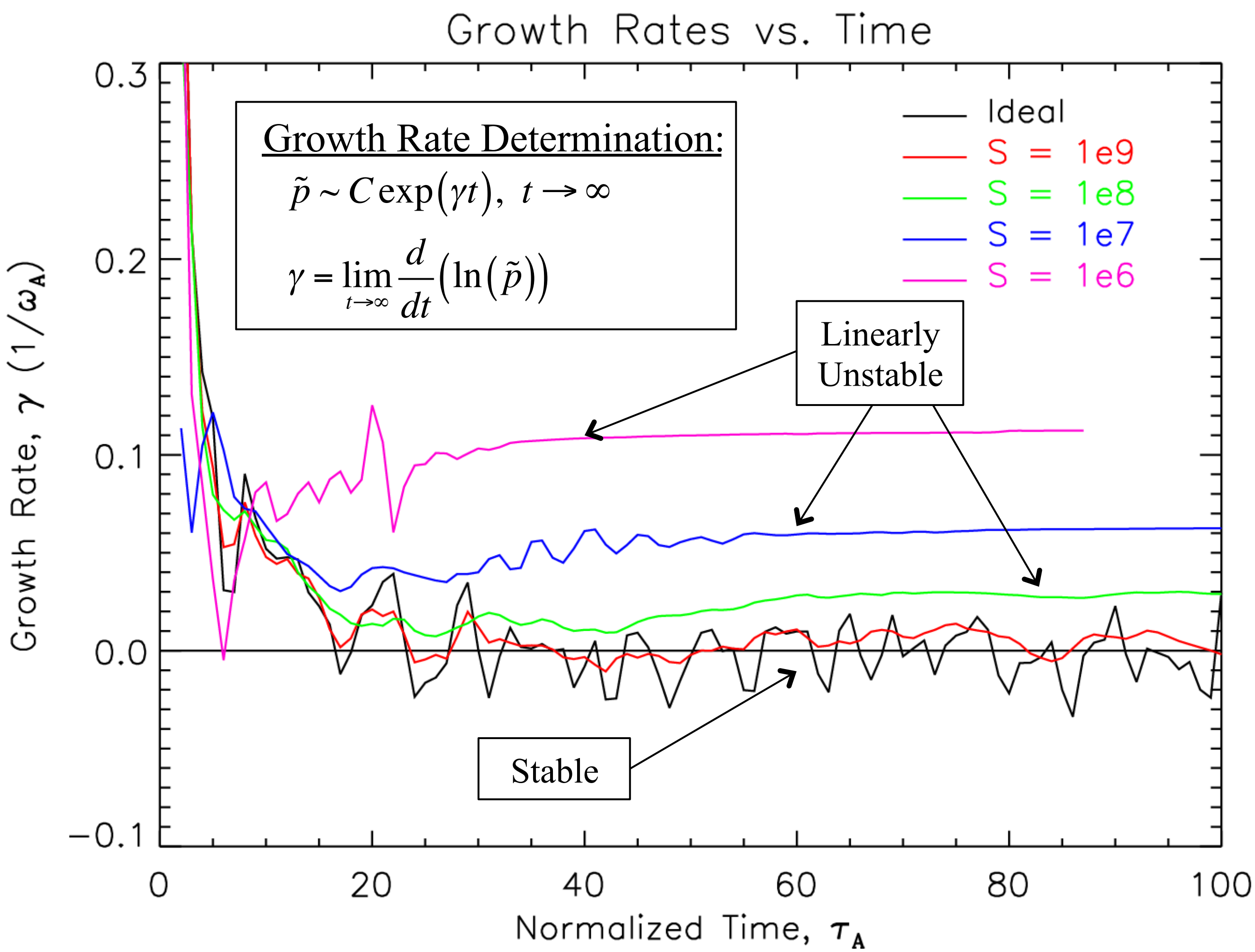
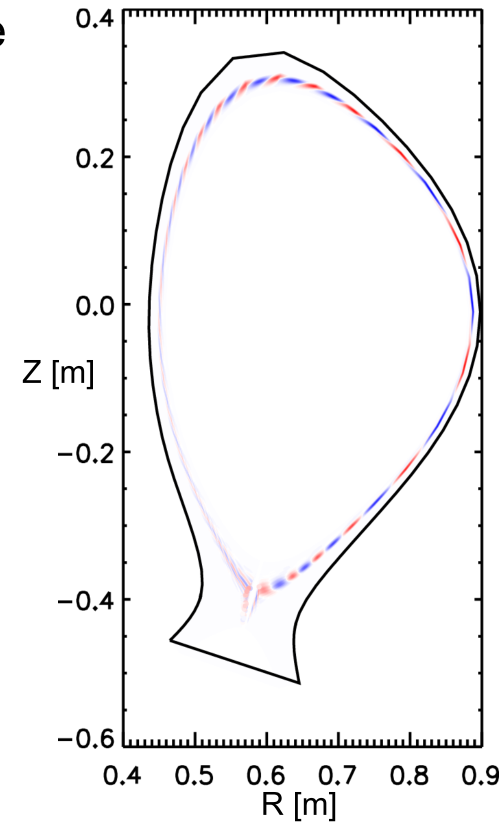
BOUT++ Calculations Show C-Mod EDA H-Modes Resistively Unstable

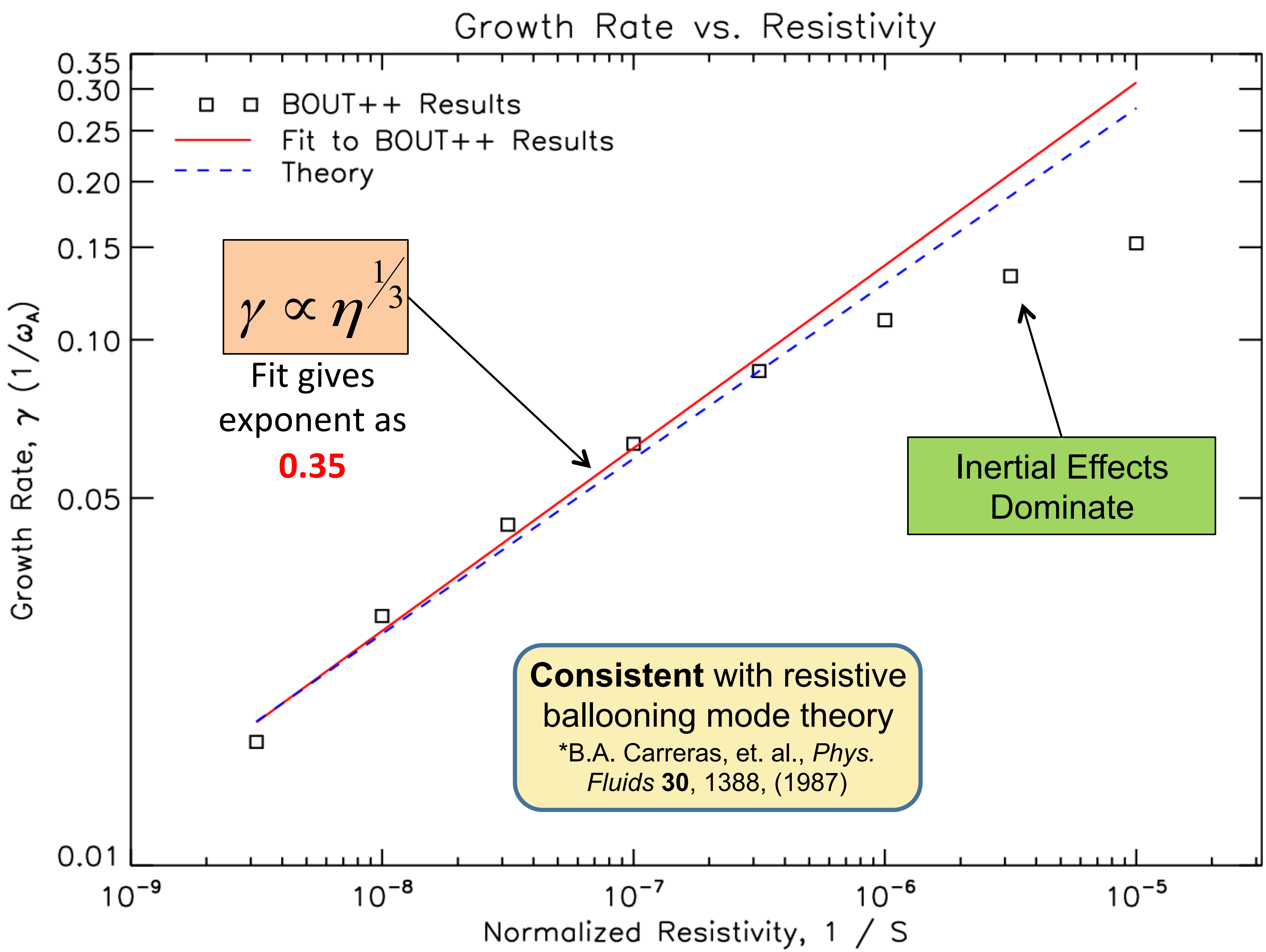
- BOUT++ calculations show that C-Mod is ***ideal*** MHD ***stable*** for typical EDA H-Modes (1110201023)
- However, such modes become *linearly* ***unstable*** when the Pedestal Resistivity is included ($S < 10^9$)



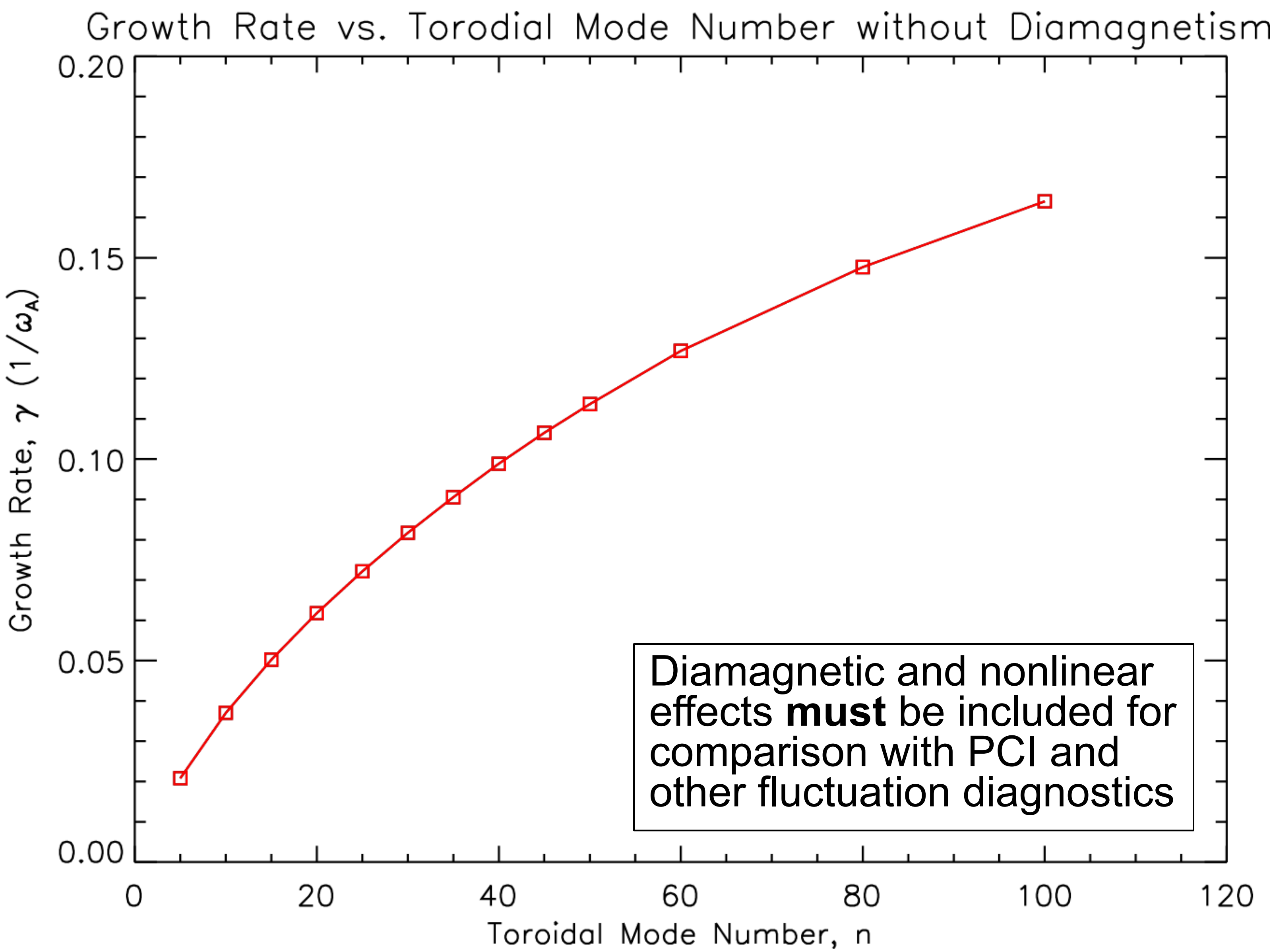


The simulated structure of C-Mod's n = 15 resistive ballooning mode

BOUT++ Computed Growth Rates are Consistent with Resistive-Ballooning Mode Theory



BOUT++ has computed the Linear Mode Spectrum for C-Mod's EDA H-Mode



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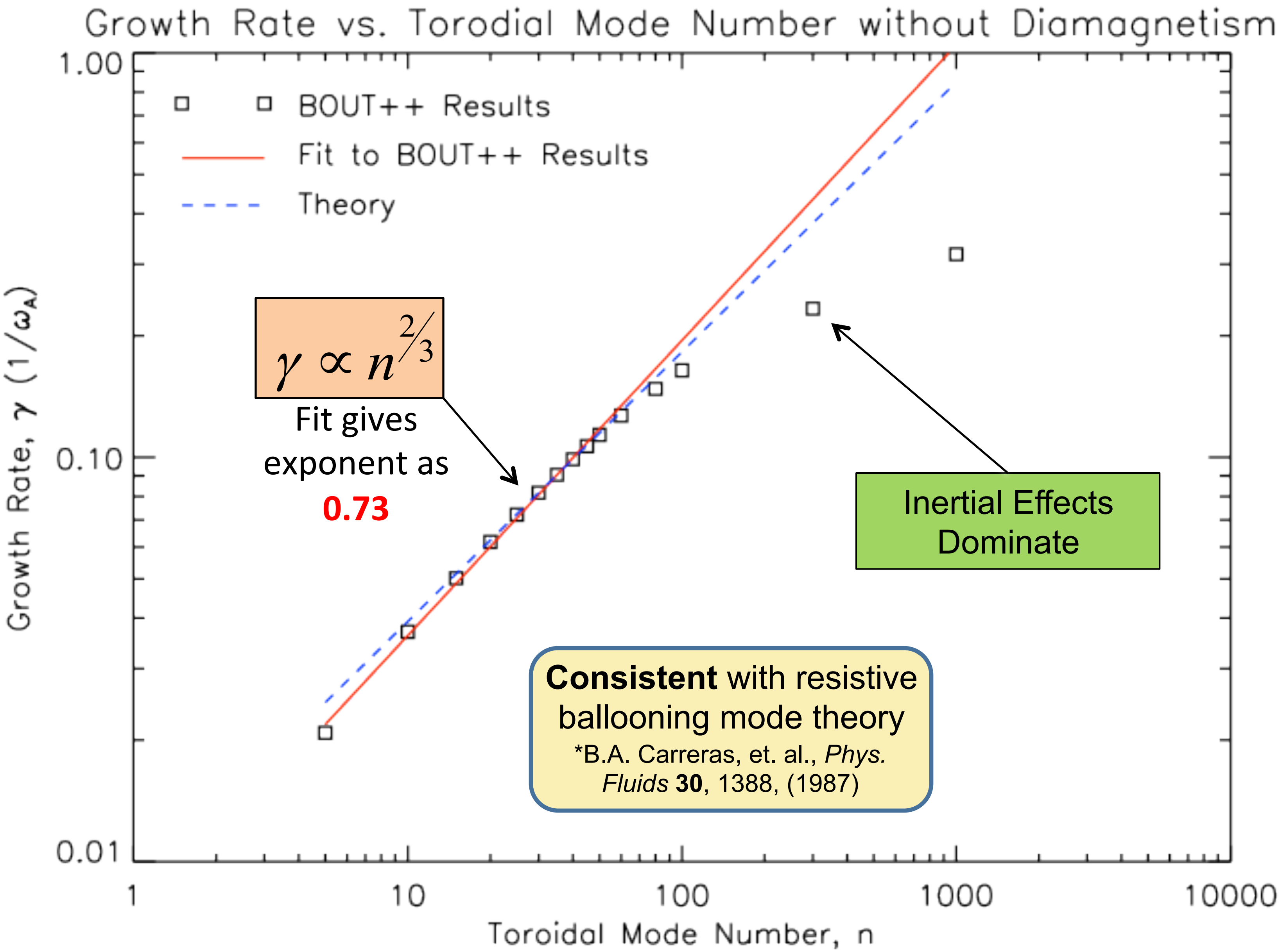

Diamagnetic Effects and an Equilibrium Radial Electric Field were Added into the Model

Reduced MHD Equations

Vorticity

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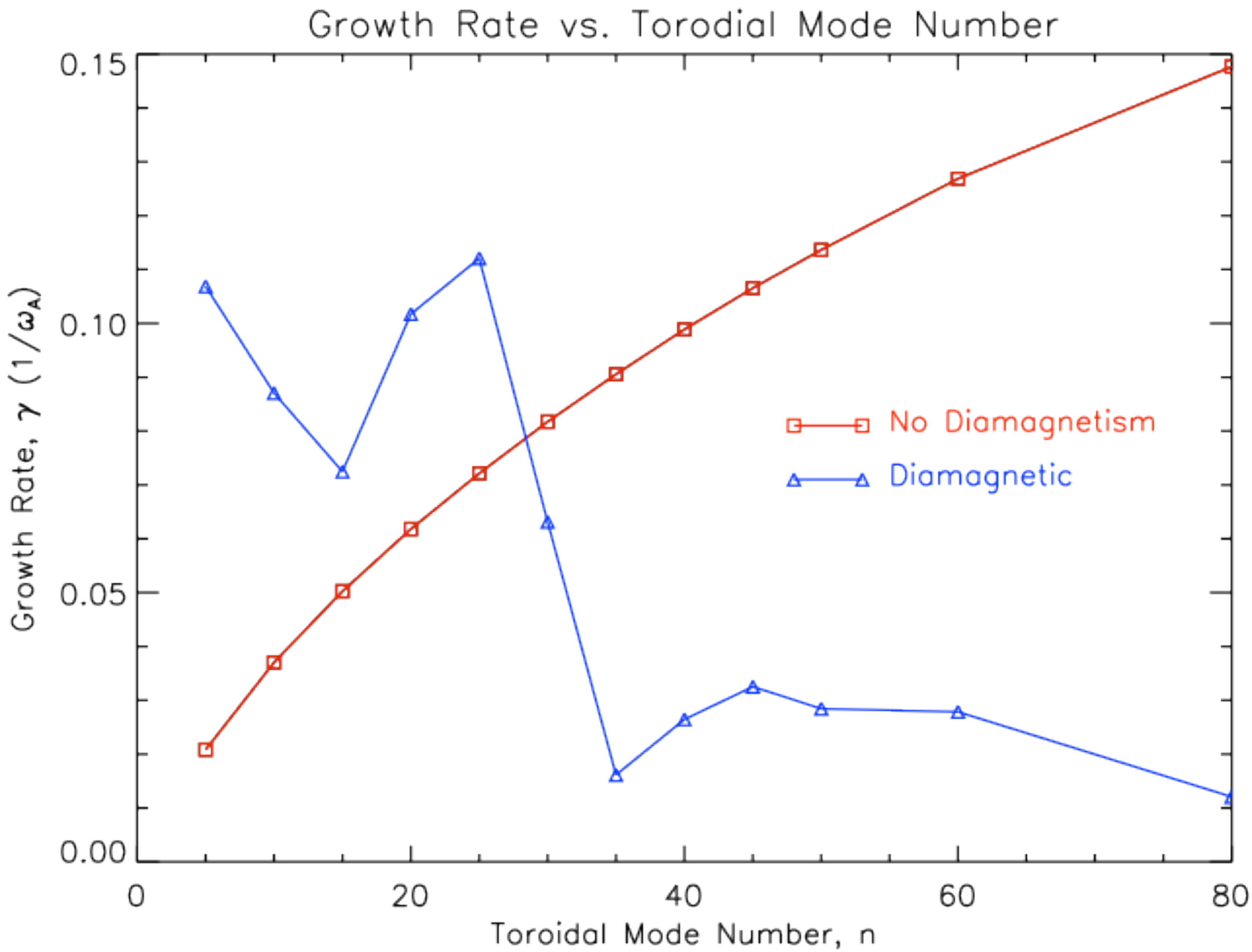
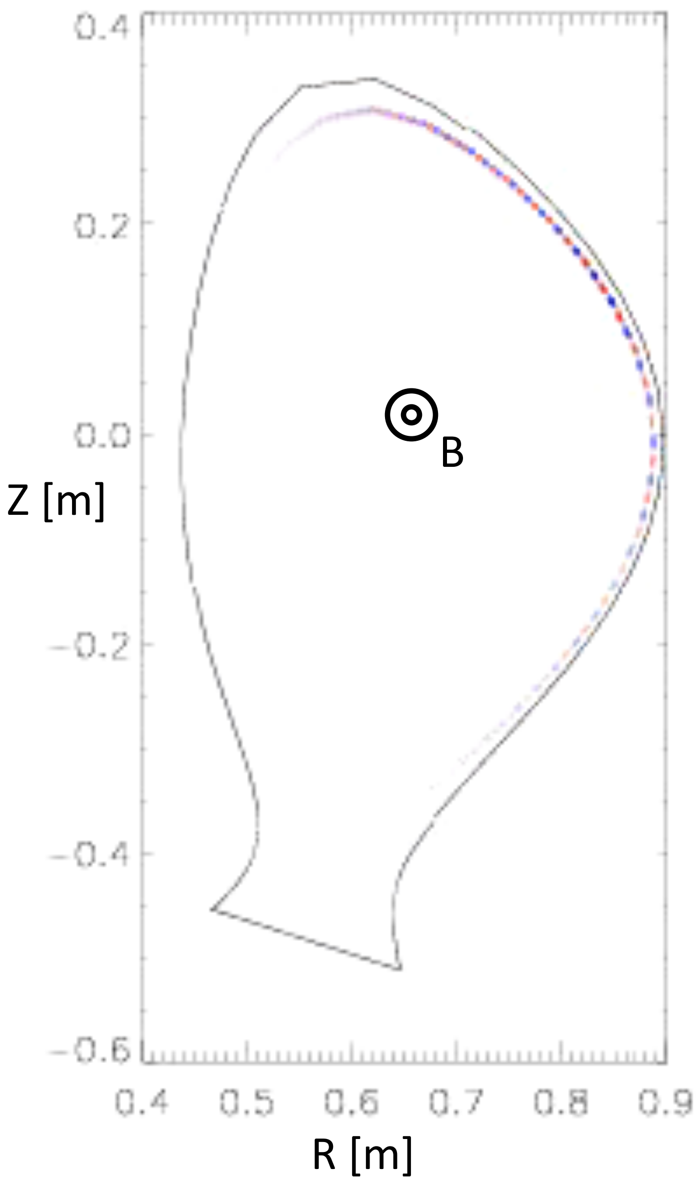
BOUT++ calculations show that Diamagnetic Effects Damp Higher Mode Numbers



The BOUT++ Computed Mode is Found to Propagate in the Electron Diamagnetic Direction



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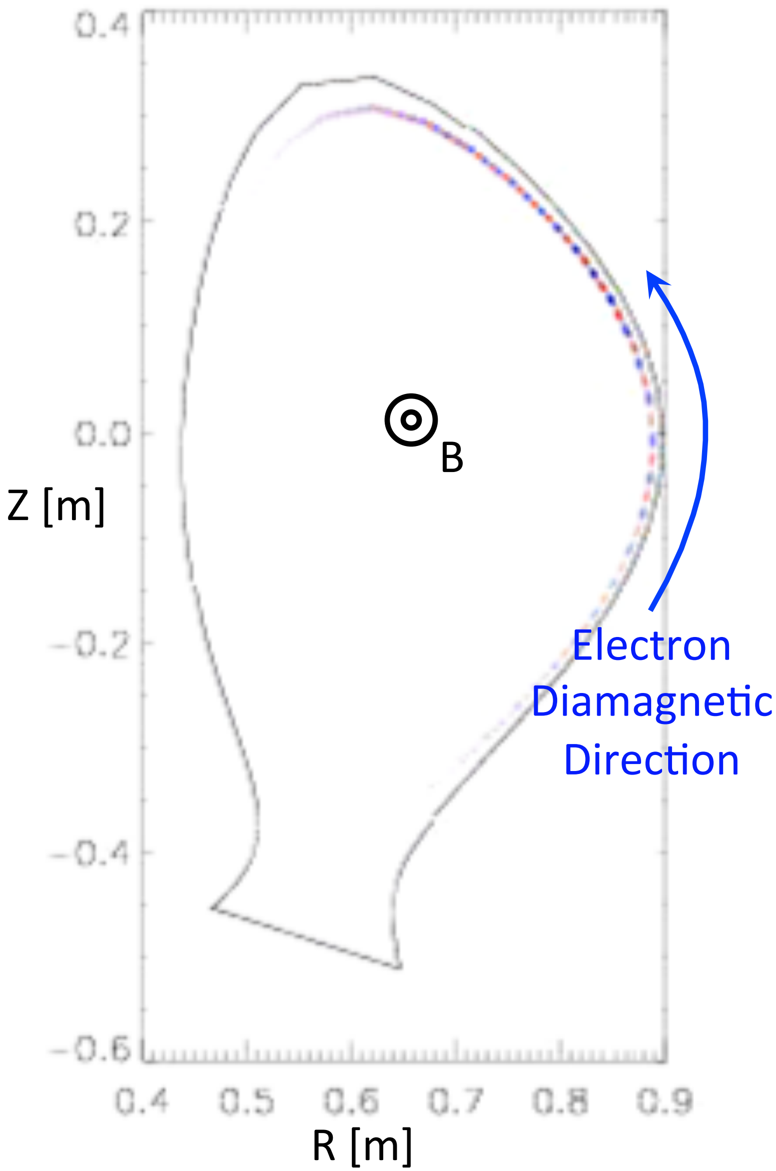
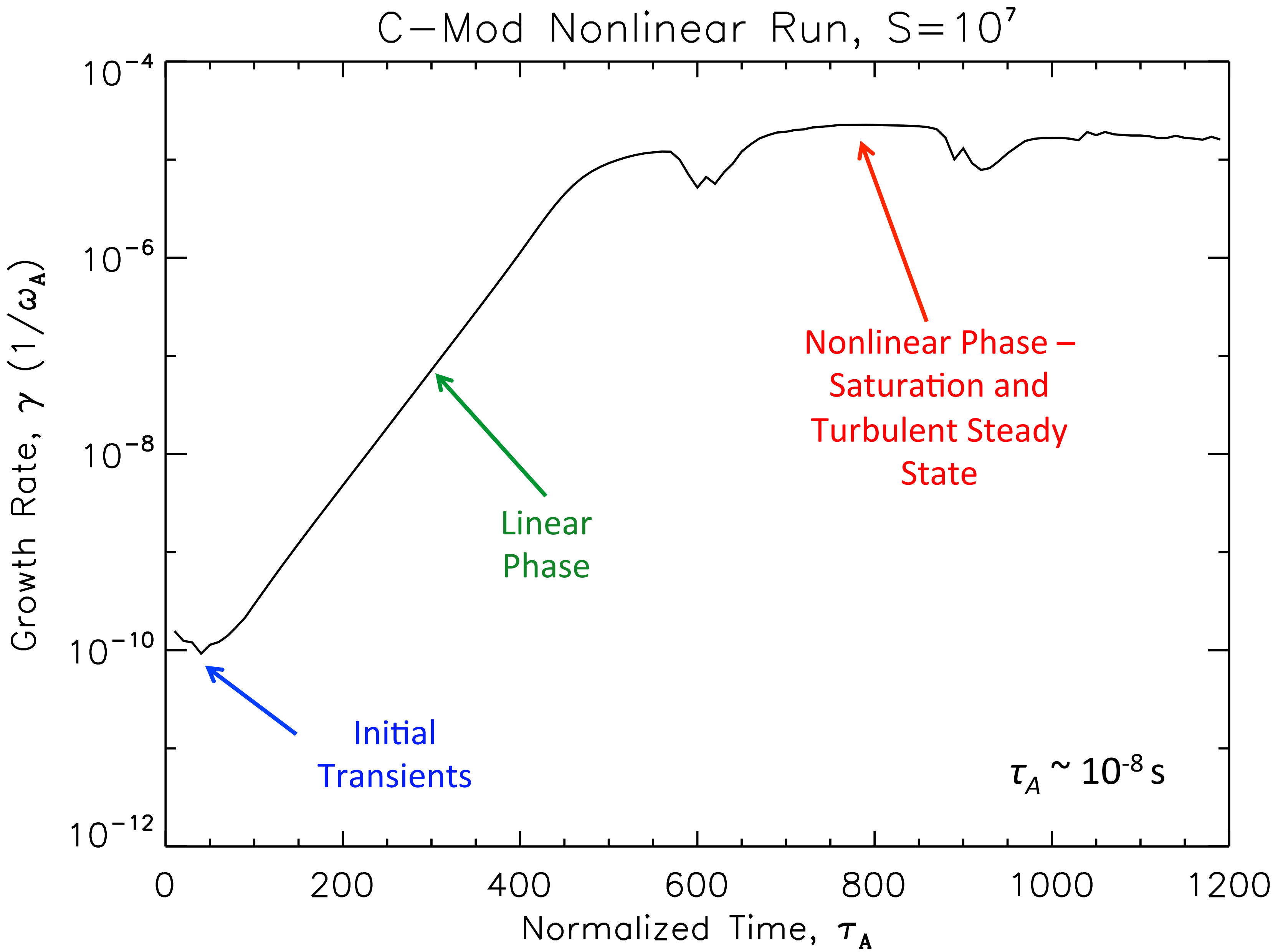


- Propagation direction **agrees** with experiment!!!
  - Experimental determination from Correlation between scanning Langmuir probes
- Must run **nonlinear** simulations to reach saturation and steady-state turbulence
  - Frequency, intensity, and localization of mode can then compared to measurements
    - PCI, Reflectometry, ECE, etc.
  - Can the QC Mode be excited and controlled by an external antenna?

Preliminary Nonlinear Simulations have begun – Mode Saturation and Turbulent Steady-State have been Observed



Conclusions and Future Work

- BOUT++ results **agree** with theory and show that C-Mod's EDA H-mode is resistively unstable
- Turbulent **steady-state** during *nonlinear* simulations has been achieved
- Incorporating **flow** into nonlinear BOUT++ simulations will allow for comparison with fluctuation diagnostics
  - The physical origins and effects of the EDA QC Mode and the I-mode Weakly Coherent Mode will be investigated
  - This effort will further the understanding of edge turbulence and its influence on tokamak energy confinement